Orbital Space Settlement Radiation Shielding

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PREPRINT

July 2015

Abstract

We examine the radiation shielding requirements for protecting the inhabitants of space settlements located in orbit. In particular, we recommend a threshold of 20 mSv[1]/year for the general population and 6.6 mGy[1]/year for pregnant women based on the most relevant existing standards and background radiation on Earth. With these thresholds we discover that space settlements in equatorial LEO (Low Earth Orbit) below about 500 km are likely to meet this standard with little or no dedicated radiation shielding, the pressure hull and structure will likely provide sufficient protection. This reduces the mass of typical orbital space settlement designs by well over 90%.

Space settlement studies in the 1970s assumed that lunar regolith with a mass equivalent to Earth's atmosphere above high altitude cities, roughly 4.5 tons per square meter of hull, would be sufficient to meet a 5 mSv/year threshold for settlers at the Earth-Moon L5 point, their recommended settlement location. Using OLTARIS, NASA's online radiation computational tool, we found this to be far too little shielding for their 5 mSv/year threshold. Even at our higher thresholds about 10 tons/m^2 of lunar regolith is required.

Fortunately, radiation shielding mass requirements can be substantially reduced by using better materials and/or by placing settlements in low Earth orbit (LEO) rather than above the Van Allen belts. Specifically, to meet the 20 mSv/year and 6.6 mGy/year thresholds our calculations suggest that 6-7 tons of water or polyethylene radiation shielding per square meter of hull is sufficient in free space; and settlements in a circular 500 km or lower equatorial Earth orbit may require little or no dedicated shielding at all. The 1970s studies assumed extraterrestrial materials would be necessary to avoid launching enormous quantities of radiation shielding from Earth. If no dedicated radiation shielding is necessary, besides being far less massive, the first

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[1] The modern measure of radiation is the Gray. The biological effect of a given level of radiation is measured in Sieverts. Conversion of Grays to Sieverts depends not only on the type of radiation involved but on the tissue being exposed. mSv stands for milli-Sievert, or one thousandth of a Sievert. mGy stands for milli-Gray, or one thousandth of a Gray. When converting from mSv to mGy, the mGy figure is always larger than the mSv for the same point. Note that in the some of the radiation tables in this paper the mSv and mGy levels are computationally 'measured' at different points.

settlements may not need extraterrestrial mining and processing. This suggests a smaller step between large LEO space stations and hotels and the first settlements.

It is important to note that there are significant uncertainties in our understanding of the effects of low-level continuous high-energy particle radiation on human tissue that need to be resolved. Also, this paper is based on numerical calculations, not physical measurements.

Introduction

This paper examines the radiation protection requirements for permanent human settlements in orbit. By our definition a space settlement is a place where, among other things, children are raised, as opposed to a space station which is more of a work camp where people go for limited periods of time for specific purposes. A series of studies in the 1970s [Johnson 1975, O'Neill 1977] suggested the feasibility of building large orbital space settlements suitable for permanent habitation including raising children. One of the system drivers was radiation, and the location chosen for settlement was the Earth-Moon L5 point[2] so that lunar materials could be used, especially for radiation shielding. Thus, for these studies, the Earth's magnetic field provided no radiation protection as L5 is well above the Van Allen belts..

Radiation levels in space are significantly higher than on Earth and this can have a number of negative effects on the human body including but not limited to birth defects, cancer, cardiovascular problems, central nervous system problems, cataracts and premature sterility [Straume 2010].

Radiation can be blocked either by shielding materials or by electromagnetic forces. The 1970s studies chose materials, and the mass of the resulting settlement designs is dominated by radiation shielding: 4.5 tons of lunar regolith per square meter of hull. This was intended to duplicate the radiation protection provided by the Earth's atmosphere, which is 10 tons/m^2 at sea level and about 5 tons/m^2 at high altitude cities. This shielding mass is far more than the structural mass, atmosphere, and interior accommodations combined. Thus, acquiring radiation shielding mass was considered one of the most difficult technical challenges in developing orbital space settlements. This drove the choice of L5 as the settlement location so that lunar materials could be used for radiation shielding. An elaborate mining and transportation system was designed to deliver large quantities of lunar regolith to L5. It should be noted that L5 is well above the protective effects of Earth's magnetosphere, and the 4.5 tons of lunar regolith turns out to be insufficient as it is not a very good shielding material (see below).

Since the 1970s there has been considerable improvement in our understanding of radiation in space and ways to reduce the impacts of that radiation, but most of the long term studies have focused on voyages to Mars, not settlement [e.g., Wilson 1997, Cucinotta 2012]. These studies have assumed a few years of exposure, minimal spacecraft mass as the vehicle must travel to Mars, and only adults on board. By contrast, settlement involves decades of exposure, the

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[2] L5 is a point on the lunar orbit equidistant from Earth and the Moon.

potential for significantly more radiation shielding mass as the settlement generally isn't changing orbit, and children and pregnant women on board.

There is one study by Straume et. al. that examines radiation shielding requirements for Mars settlement [Straume 2010]. However, unlike orbit, Mars has ample materials for radiation shielding on the surface so the focus is on transit of settlers to Mars, which is on the order of a half year. Staume's study examined the limiting threat, i.e., what is the most serious risk that, if one has enough shielding to reduce that risk to acceptable levels, all other threats will be taken care of.

Studies of non-human primates found that oocytes[3] are extremely radiosensitive during gestation. At high radiation levels we expect an effective early onset of infertility. Oocytes are not replenished during a woman's lifetime and there are a limited number of them, all present at birth. As a result, in our study, we looked at radiation damage to female ovaries and assumed that if these can be kept healthy then radiation to other organs and tissue will be acceptable. We also look at the radiation threat to the developing embryo and fetus during pregnancy and assume that acceptable levels here are also acceptable for children.

Radiation in Space

There are three major classes of dangerous radiation in space [Schimmerling][Clement 2012]:

The first class is caused by solar storms. These happen 5 to 10 times per year, except near a solar minimum [Cucinotta 2012]. These storms are directional, going outward from the Sun in a relatively small area, last for several hours at peak exposure rates, and are dominated by protons with an energy of one MeV up to a few hundred MeV. Fortunately, protons have small mass (comparatively) and are relatively easily blocked. Severe storms, however, may require extra shielding for short periods of time. Also, dangerous solar storms are very rare. Only five since 1955 have been strong enough to endanger astronaut health when protected by normal spacecraft shielding [Clement 2012].

The second class of dangerous radiation consists of galactic cosmic rays (GCR). If these are adequately shielded, then solar storms will cause few problems. GCR are made up primarily of nuclei with no electrons, can travel at relativistic speeds, and are omni-directional. Energy varies from less than one MeV/u[4] to more than 10,000 MeV/u with a median of perhaps 1,000 MeV/u. The level of GCR in the solar system varies with the solar cycle, with periods of low magnetic activity allowing more GCR into the inner solar system, but this effect is limited to energies less than roughly 2,000 MeV/u [Cucinotta 2012]. While most of the nuclei involved have low atomic number, the most dangerous of the GCR particles are heavy ions such as iron nuclei. Fortunately, GCR is at a fairly low level.

[3] The cells that develop into eggs.
[4] MeV/u stands for million electron volts per neutron or proton.

There is a third class of space radiation which is relevant to settlements in Low Earth Orbit (LEO). This consists of trapped electrons and protons in the Van Allen belts [Schimmerling] which can result in somewhat high radiation levels in relatively low Earth orbit (very roughly 1,000 - 60,000 km). However, these are light particles (electrons and protons) that can be stopped by minimal shielding, such as a settlement hull. This radiation can cause problems for settlers performing spacewalks for repairs or recreation.

Radiation and the Human Body

Unfortunately, much of what we know about radiation effects on the human body come from studies of the victims of the Hiroshima and Nagasaki atomic bomb attacks, involving very high radiation levels for short periods of time, which doesn't necessarily generalize to long term exposure to low level GCR. There have also been a number of studies of people exposed to radiation at work, e.g., nuclear power plant operators. These indicate a possible small effect on fertility in both men and women [Straube 1995, Doyle 2001]. In a survey paper, Brent found that to negatively affect pregnancy and fetal DNA, a fairly high radiation level is required, well above our proposed 20 mSv/year and 6.6 mGy/year thresholds [Brent 2012]. However, these studies do not involve the high energy massive particles that characterize the most dangerous parts of GCR.

Radiation studies on animals are usually limited to short time periods because that is easier to do. Short periods of higher flux are used to simulate lower levels for longer periods. So, due to the nature of the data, relatively little is known about the biological effect of long periods of low-level high-energy high-mass particles such as relativistic iron nuclei. Thus, the conversion of low GCR radiation levels to biological effectiveness must be viewed with some suspicion. Improved data and understanding may affect the results presented here.

The problem is further confused by secondary particles. When an iron nucleus (or other heavy particle) passes through a material and strikes another nucleus, a shower of smaller secondary particles is created. These can be more damaging than the original particle, just as a shotgun wound can be more serious than a wound from a rifle bullet. Thus, a small amount of shielding can worsen radiation damage by creating secondaries, so shielding must be thick enough to absorb most of the secondaries as well.

We now determine acceptable radiation standards for adults and pregnant women. We then quantify this expected radiation levels in various situations with OLTARIS, NASA's web front end to sophisticated radiation modelling software [OLTARIS 2011, OLTARIS 2014].

Radiation Threshold for Space Settlement

The amount of shielding thought necessary to protect settlers from the space radiation environment depends heavily on the threshold chosen. We have chosen 20 mSv/year for the general population, with caveats, to match the most relevant data points (see next paragraph), and 6.6 mGy/year for pregnant women, with less certainty. This is well above the 5 mSv/year

used in the 1970s studies, which is, in our opinion, unnecessarily low. These thresholds are well below the limit for deterministic radiation effects[5], 500-2,000 mGy [Clement 2012] (depending on the tissue) and is intended to limit stochastic effects such as cancer.

We first examine the 20 mSv/year limit for the adult population followed by a discussion of the 6.6 mGy/year limit for pregnant women.

Radiation Threshold for Adults (20 mSv/year)

The International Commission on Radiological Protection (ICRP) recommends a 20 mSv limit for occupational radiation exposure [Wrixon 2008]. This is also the threshold used by the Japanese government to determine which residences may be re-occupied after evacuations due to the Fukushima nuclear power plant accident [McKirdy 2014]. 50 mSv/year is the threshold for radiation workers in the U.S. [Space Radiation Analysis Group 2014]. The annual limit for US astronauts is 500 mSv/year in the blood forming organs with a lifetime cap of 10,000 - 30,000 mSv for women and a higher limit for men [Space Radiation Analysis Group 2014].

20 mSv/year is considerably above the average background radiation in the U.S., 3.1 mSv/year (not including medical X-rays, etc.) [Linnea 2010, NRC 2010]. However, this is an average, and much higher levels exist locally. There are several large regions of Europe, particularly in Spain and Finland, with levels over 10 mSv [World Nuclear Association 2014] and there are inhabited parts of the world with much higher levels with no known major negative effects.

For example, the highest recorded background radiation on Earth is in Ramsar, Iran, where monitored individuals have received an annual dose up to 132 mGy/year, far above our 20 mSv/year threshold [Ghiassi-nej 2002][6]. Other high natural radiation areas include Yangjiang, China, Kerala, India, and Guarapari, Brazil, with no apparent major negative effects.

Thus, it seems that 20 mSv/year is a reasonable level to use for the present study, being aware that additional research is needed and this threshold may need to be changed as better data and theory become available.

Radiation Threshold for Pregnancy (6.6 mGy/year)

There is reason to believe that the radiation threshold should be lower for the embryo and fetus. We have chosen 5 mGy/pregnancy (6.6 mGy/year) primarily based on data and recommendations found in ICRP publications.

The ICRP has developed guidelines for acceptable radiation levels for (among other things) the embryo and fetus. An ICRP publication [Wrixon 2008] established radiation thresholds based

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[5] A deterministic radiation effect is one that will almost certainly happen soon, as opposed to stochastic effects such as contracting cancer years later.

[6] For a given level measured in Grays the value in Sieverts is as great or greater at a given point, depending on the tissue in question. Note that in the tables below this appears to be violated because the computational measurements are done at different points.

on [Valentin 2000] and [Valentin 2003] for various radiation threats to the fetus and embryo and published these values as indicating the dose at which problems have been observed:

Effect	mGy threshold
Pre-implantation lethality	100
Introduction of malformations	100
Severe mental retardation	300
Negative effects on IQ	100
Life-time cancer risk 3x increase	100

Table 1. Data from [Wrixon 2008]. The rows list possible effects of radiation exposure before birth. The numbers are a summary of radiation thresholds for pregnant women as part of recommendations for radiation dose, which is very relevant to medical decisions for pregnant women (e.g., whether to have an x-ray or not).

Notice that the values given here are in mGy, a measure of radiation, not mSv, a measure of biological effect. This is because there is presently no meaningful way to judge the correctness of the tissue-weighting factors used to convert radiation (in mGy) to biological effect (in mSv) [Valentin 2003] for the fetus or embryo. For example, the effect of a given dose of radiation on the fetus depends greatly on the when it occurs [Valentin 2003].

As the effects of radiation during pregnancy is a complex subject. We have abstracted the most relevant sections of the ICRP pregnancy-related publications [Valentin 2000] and [Valentin 2003] for readers who would like a more detailed examination:

- Many effects of prenatal radiation do not manifest with less than 100 mGy exposure, although a few show up at 50 mGy [Valentin 2003]. However, changes in avoidance time were observed in rodents were observed whose mothers had been injected tritiated water causing the fetus to absorb at least 46 mGy [Valentin 2003] paragraph 173.
- [Wrixon 2008] recommends a 1 mSv/pregnancy limit for women with occupational radiation exposure and [Valentin 2000] recommends 1 mGy/pregnancy. This is in addition to the background radiation, which, as noted above, is much higher than than 5.6 mGy/year (which would bring the total to our 6.6 mGy/year limit) in many places on Earth.
- [Valentin 2003] notes one study suggesting that 10 mGy of medical radiation[7] to the fetus may result in an additional child cancer death for each 1,700 fetuses exposed (in addition to the 4-5 one would otherwise expect). However, other studies suggest that the childhood cancer rate due to 10 mGy would be less than this.

[7] In cases where the mother needs radiation-based diagnostics or treatment.

- [Valentin 2003] Table 4 indicates that fetal absorbed dose below 5 mGy per pregnancy (our suggested limit) shows no increase in childhood cancer or increase in malformations. However, a dose of 10 mGy/pregnancy has a slightly higher risk of childhood cancer.
- Nuclear bomb victims in utero showed sharp increases in severe mental retardation with doses >= 200 mGy when 8-15 weeks pregnant and >=600 mGy for 16-25 weeks, but not below these thresholds or at other points in pregnancy [Valentin 2003] figure 5.1.
- “There were 10 cancer deaths among 1,078 prenatally exposed people in Hiroshima and Nagasaki … The 807 people with estimable in-utero doses of at least 10 mSv included eight cancer deaths…” at ages 0-46 years. [Valentin 2003 paragraph 376.
- 100 mGy or less can cause pre-implantation death during some radiosensitive stages, but this is far above what would be experienced if radiation is limited to 5 mGy/pregnancy and pre-implantation lasts only a few days [Valentien 2003] paragraph 409.
- In a very large study[8] of children whose mothers were x-rayed during pregnancy it was found that there were 200-640 excess cancer deaths per 10,000 people per 1,000 mGy ages 0-16. The corresponding figure for atomic bomb victims was 70 [Valentin 2003] paragraph 397. If there is no threshold, and the effect is linear to zero, that would imply 0.35-3.2 cancer deaths per 10,000 people at 5 mGy exposure if spreading out the dose does not reduce effects.
- The ICRP does not recommend pregnancy termination at fetal exposures less than 100 mGy from medical sources [Valentin 2000].
- There is evidence that cyclotron neutrons cause more cancers than x-rays and gamma-rays, the radiation used in most of the studies referenced here [Valentin 2003] paragraph 280. There is essentially no data for low-level GCR effects during human pregnancy.
- Most of the data available are for short periods of high radiation (atomic bombing, medical x-rays) and there are many experiments with rodents showing that negative effects are reduced if the same amount of radiation is delivered over a protracted time period [Valentin 2003] paragraph 424, which is the case for space settlers.

For comparison with Earth-bound pregnancies and cancer:

- When pregnant women are exposed to only Earth background radiation (3.1 mSv average in the US) there is a 15% spontaneous abortion rate, 2-4 percent chance of major malformations, a 4% chance of retardation and 8-10% chance of genetic disease [Valentin 2003].
- Lifetime cancer risk today is about 1 in 3 and cancer caused death about 1 in 5 [Valentin 2003].

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[8] The Oxford Survey of Childhood Cancers, aka OSCC [Gilman 1988]. Note that this survey had some methodological problems, such as depending on the mother’s memories for x-ray history.

All this suggests that it might be wise to keep prenatal exposure to significantly less than 100 mGy over nine months and that 5 mGy per nine month pregnancy may be a good threshold, which translates to about 6.6 mGy/year. This is 20 x less than the threshold for considering pregnancy termination and is the highest level with no reported increase in childhood cancer in [Valentin 2003] Table 4. Note that if this level is exceeded by a small amount, additional shielding could be temporarily added to the homes of pregnant women to meet the threshold.

We assume that the combination of thresholds for ovaries and the fetus will be protective for children as well. This will require a research program to verify. The other big unknown is that most of these data were gathered to be relevant to medical radiation procedures, such as x-rays, which are much different from the high energy, high mass GCR particles we are primarily concerned with. Also, medical radiation normally comes in short, high doses, not long term low dose. Most of the rodent radiation studies use doses that are intended to model medical radiation exposure.

It should also be noted that there is some evidence that low levels of radiation stimulate an adaptive response from the human body that reduces the radiation damage one might otherwise expect [Ghiassi-nej 2002]. There are similar results for rodents in some circumstances [Valentin 2003]. This is hard to study and should not be considered definitive, but may make the low levels of GCR expected by space settlers more acceptable than one might otherwise expect.

Clearly, people moving from Earth to a space settlement can expect to be exposed to higher levels of radiation, but this can also be true for people moving from place to place on Earth.

Radiation Shielding Materials

The best shielding materials for GCR are dominated by hydrogen. This is because heavy positively charged particles with a lot of energy are stopped primarily by electromagnetic interaction with electrons rather than collisions with nuclei [Ziegler 1988]. Indeed, as we have seen, collisions with shielding nuclei can increase effective radiation dose due to the creation of secondary particles. As a particle passes through good-quality shielding, large numbers of electrons are pulled out of position, transferring energy from the particle and eventually bringing it to rest. Liquid hydrogen might be the ideal shielding material from this perspective, but it is difficult to handle and maintain. Among the best practical materials are polyethylene and water [Wilson 1997].

Polyethylene consists of long strands of carbon atoms each bonded to two hydrogen atoms (except at the ends). It is a little better than water because carbon nuclei are smaller than oxygen, making for fewer collisions and less mass for the same number of hydrogen atoms. Note that many asteroids are rich in carbon compounds and water.

Lunar regolith, which has little hydrogen, is a poor radiation shielding material. This is illustrated by Table 2 which shows the radiation level expected in “free space” (above the Van Allen belts

in OLTARIS terminology), given the mass of the shielding and the type of material. Note that a much greater mass of lunar regolith is necessary to bring radiation levels below 20 mSv/year than with polyethylene or water.

	polyethylene		water		lunar regolith	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr	mSv/yr	mGy/yr
1	193	85	199	86	274	109
2	136	52	146	54	261	82
3	90	31	100	34	221	62
4	57	18.5	66	21	172	48
5	35	10.8	42	12.5	126	37
6	20.9	6.3	26.3	7.5	89	28
7	12.2	3.6	16	4.4	61	20.9
8					40	15.1
9					26.1	10.5
10					16.6	7.1

Table 2: Comparison of shielding materials in free space. The rows indicate yearly radiation levels at a given shielding mass. The first column lists tons of shielding per square meter, the other columns list different materials and measures. The mGy columns are a (computational) measure of radiation taken inside shielding, the mSv columns are radiation absorbed by human ovaries. The red color indicates that values are less than 20 mSv/year. Note that the 6.6 mGy/year level for pregnant women is also met (or nearly so for lunar regolith). Note also that polyethylene is a bit more effective than water, and both are quite a bit more effective than lunar regolith. All values are calculated by OLTARIS.

Space Radiation as a Function of TIme

The amount of radiation experienced in space varies with time, in great part due to the magnetic activity of the Sun, and OLTARIS simulates this effect. The less solar magnetic activity, the stronger the GCR in Earth orbit as the Sun's magnetic field deflects incoming charged particles. All of the data presented here were calculated for a somewhat low solar activity period from 17 June 1977 to 17 June 1978 and are thus conservative. However, there are even lower radiation times, such as 17 June 2008 to 17 June 2009. For adults only the average dose over many

years is relevant, so the 1977 time period is appropriate. However, for fetus and embryo only the 9 months while pregnant matter so exceptionally high periods of radiation could be a problem.

Location Influence on Radiation Shielding Requirement

The radiation experienced by space settlers depends a great deal on location. For example, on the surface of Mars or the Moon approximately 50% of the GCR is blocked by thousands of km of rock. Also, on Mars, there is some protection from the atmosphere, although not much. Furthermore, settlements can be located in caves or buried with local materials which are plentiful. Local materials can also be used by orbital space settlements when built co-orbiting with asteroids. This paper will focus on a strategy suitable for the first space settlements: placing them in equatorial low Earth orbit (ELEO) to take advantage of the Earth's magnetic field and the Earth itself.

Radiation levels in LEO are influenced by both the altitude of the orbit and the inclination. The lower a settlement is the more radiation protection it receives both from the Earth itself and from Earth's magnetic field. Very low inclinations, i.e., very close to 0, experience much less radiation due to the shape of the magnetic field. See Table 5 below.

Radiation in Equatorial LEO

Table 3 contains the yearly radiation levels calculated for five orbital altitudes (600, 700, 800, 900, and 1000 km) for zero inclination circular equatorial orbits as a function of polyethylene shielding measured in tons of material per square meter of hull. Note that at 600 km one ton of shielding is more than adequate to meet the 20 mSv/year and 6.6 mGy/year limits. The shielding required to meet these limits rises with altitude as the Earth blocks less of the sky and the magnetic field weakens.

	600 km		700 km		800 km		900 km		1000 km	
tons/ m^2	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy
1	14.2	5.2	25	10	109	60	238	135	409	234
2	14.1	4.9	18	5.9	39	9.8	158	72	115	23.7
3	12.1	4.1	14	4.7	23	6.4	36	8.9	55	12.4
4	9.5	3.2	11	3.6	14.7	4.3	20	5.3	28	7
5	6.9	2.3	7.8	2.5	9.5	2.8	11.9	3.3	15.5	4.1

Table 3: Yearly radiation levels calculated for five orbital altitudes for circular equatorial orbits in both mSv/year (human ovaries) and mGy/year (outside the

body). Rows are for levels calculated for polyethylene shielding in tons per square meter of settlement hull. The columns are radiation levels at different altitudes and different measures. Red indicates that the level meets our 20 mSv/year and 6.6 mGy/year thresholds. All calculations use OLTARIS.

Noting that at 600 km with a single ton of shielding the radiation expected, 14.2 mSv/year, is well under the 20 mSv/year limit, we did additional calculations at 500 and 600 km using very small amounts of shielding. The results are in Table 4:

shielding	500 km		600 km	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	16.7	10.2	23.4	1,559
0.01	16.3	3.6	21.7	101
0.025	15.6	3.7	19.8	50.6
0.05	14.6	3.9	17.5	21.8
0.075	13.9	4	16.1	12.5
0.1	13.3	4	15	8.9
0.15	12.5	4.1	13.6	6.1
0.2	11.9	4.2	12.9	5.3
0.25	11.6	4.3	12.5	4.9
0.5	12	4.6	12.6	4.9
0.75	12.8	4.8	13.4	5.1
1	13.3	4.9	14.2	5.2
1.25	13.7	5	14.4	5.2
1.5	13.8	4.9	14.5	5.2

1.75	13.7	4.8	14.4	5.1
2	13.5	4.7	14.1	4.9

Table 4: Yearly radiation levels calculated for circular equatorial orbits at 500 and 600 km altitude. The rows are for tons of polyethylene shielding with the exception of the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot calculate zero shielding levels). The columns are radiation levels at different altitudes and different measures. Red indicates that the level meets the 20 mSv/year limit and the 6.6 mGy/year limit for pregnant women. All calculations by OLTARIS.

Table 4 suggests that for settlements in low equatorial orbit (at 500 km), no shielding mass is required to meet the 20 mSv/year and only a tiny (equivalent to polyethylene 0.01 ton/m^2) amount to meet the 6.6 mGy/year threshold. Even the minimal shielding provided by a pressure hull should be more than sufficient to meet the pregnant woman threshold. This has radical implications for space settlement as discussed below.

There is a very high radiation level (mGy/year column) with no shielding at 600 km. This is mostly trapped protons that can be easily shielded as is seen from the rapid drop-off when small amounts of shielding are added. Note that at 600 km below 50 kg/m^2 shielding the mGy reading is higher than mSv reading because measurements are taken at different places. For mSv this is the ovaries, for mGy it is just inside the shielding and does not reflect shielding by tissue around the ovaries.

The radiation levels are not monotonically decreasing with increased shielding due to secondary particles created by collisions between incoming particles and shielding material. For example, There is a steady rise, at 500 km, of the mGy/yr column from 0.01 to 1.25 tons/m^2. A rise is also seen in the mSv/yr column above 0.25 ton/m^2. This indicates that secondary radiation produced by the hull and interior materials will increase the radiation levels experienced compared to less shielding, but not enough to exceed the our limits.

Note that there are local minima and maxima in radiation levels at 600 km as well. For example, there is a local minimum at 0.25 tons shielding and a local maximum at 1.5 tons, with radiation increasing between the two in the mSv/yr column. The minimum is caused by the shielding blocking protons and the maximum by unabsorbed GCR secondary radiation which causes more damage than the primary particles.

Figure 1 illustrates the physics behind this effect.

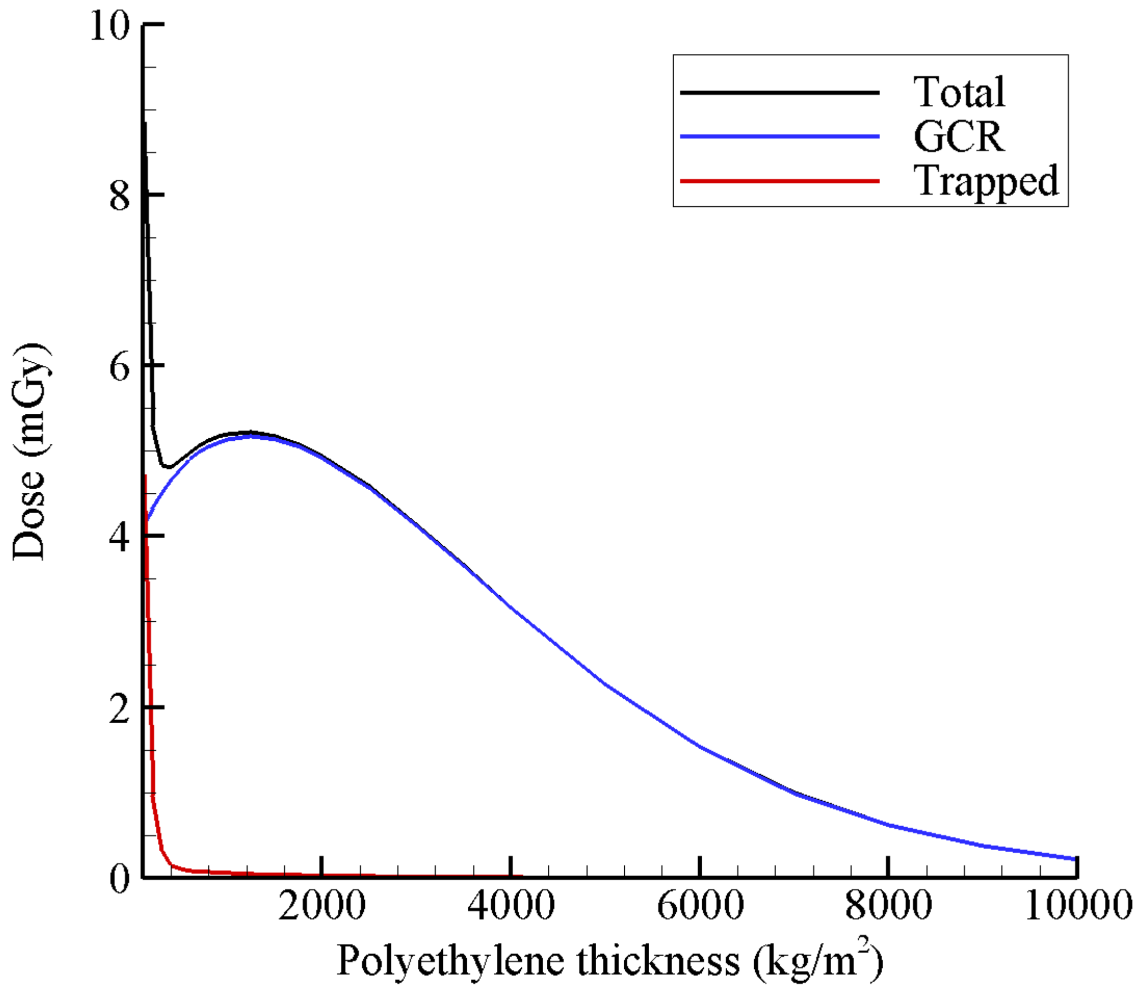


Figure 1: The trajectory was circular at 600 km and 0 degree inclination. The trapped proton component (red line on plot) consists mainly of lower energy protons that are stopped with little shielding. The dose profile from this part of the environment falls off rapidly with depth as one might expect. Image credit NASA.

The GCR component (blue line on plot) consists of high energy protons, alpha particles, and heavy ions. However, the GCR in LEO is much different than in free space, especially at 0 degree inclination. At this low inclination, only the most energetic GCR make it through the geomagnetic field. These high energy particles initiate nuclear interactions in the shielding that produce secondary particles, leading to an increase in exposure. You can see the dose increases until around 1.5 tons/m^2, and gradually declines thereafter. This behavior is analogous to the so-called Pfotzer maximum observed in the Earth's atmosphere [Slaba 2014].

Orbital Inclination and Radiation Levels

All of the radiation data examined so far are from over the equator. This is important because radiation levels for orbits away from the equator can be a great deal higher. To understand the effect of orbit inclination note that there is a region of high radiation near the equator called the South Atlantic Anomaly [Schimmerling] shown in Figure 2. The effect of inclination can be seen in Table 5, and it is dramatic: space settlements in inclined orbits require multiple tons of water shielding to meet the 20 mSv/year threshold even at fairly small inclinations. This is because equatorial orbits bypass most of the South Atlantic Anomaly. Clearly, from a radiation perspective, LEO settlements should be in equatorial orbits if at all possible.

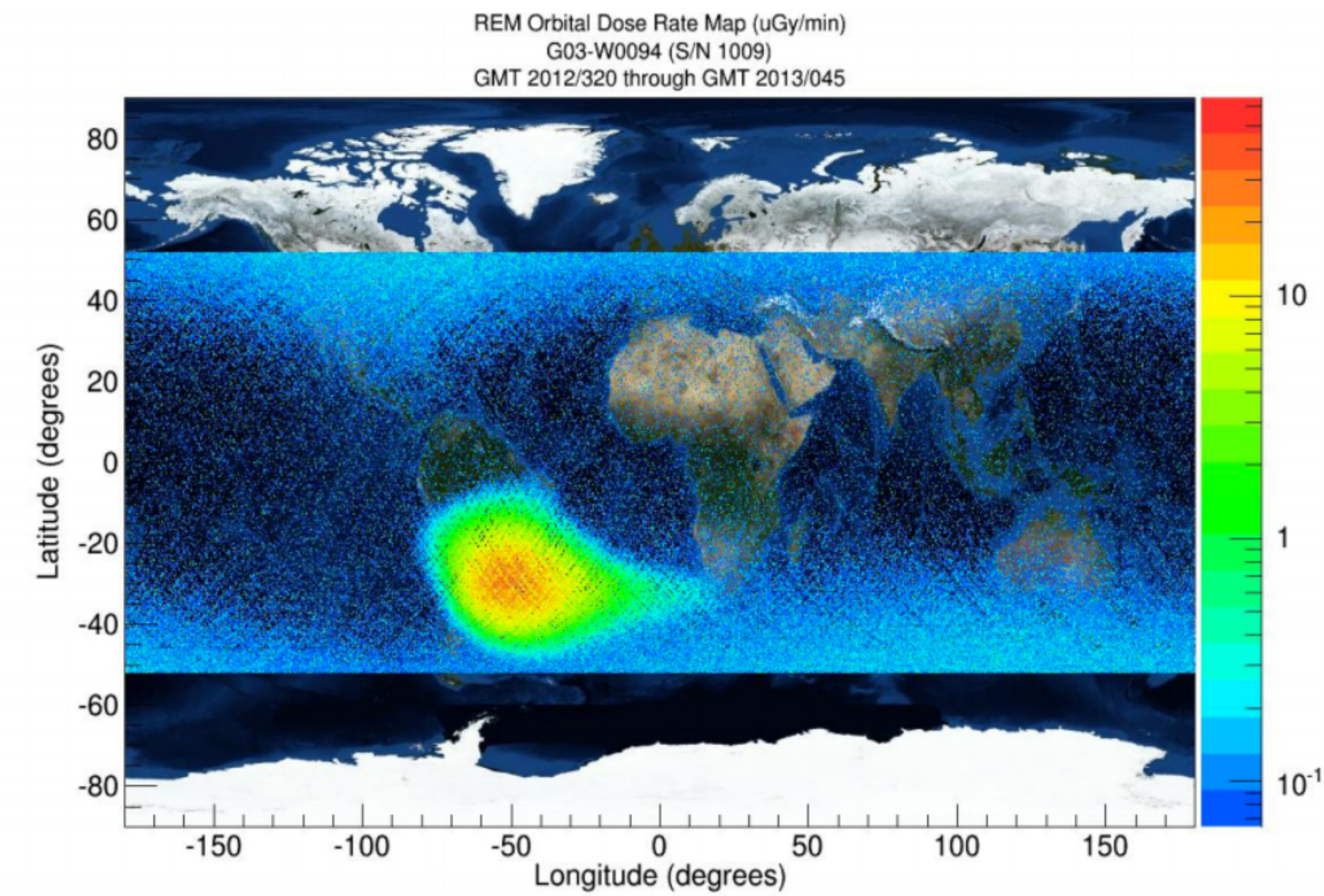


Figure 2: Radiation measurements taken on the ISS (International Space Station). Note the high levels of radiation over the South Atlantic and much of South America and very low levels near the equator. These low levels are well below our 6.6 mGy/yr threshold, but the ISS orbit is around 400 km, somewhat below the altitude of the computational data presented in the paper. Image credit NASA.

Mass (tons/m^2)	0° (mSv/yr)	15° (mSv/yr)	30° (mSv/yr)	45° (mSv/yr)	60° (mSv/yr)	75° (mSv/yr)	90° (mSv/yr)
0.25	14.6	262.8	636.0	424.1	345.0	335.5	334.0
0.5	12.1	112.1	253.5	178.2	164.0	168.7	170.3
1	13.2	43.4	88.7	79.1	90.3	100.2	102.7
2	14.0	21.6	36.7	45.5	58.9	66.4	68.3
3	12.6	16.4	25.1	33.2	42.4	47.1	48.3
4	10.3	12.3	17.6	23.5	29.4	32.2	32.9
5	7.9	8.9	12.1	16.1	19.6	21.3	21.7
6	5.7	6.3	8.2	10.7	12.7	13.7	13.9

Table 5. This shows the effect of inclination and shielding on radiation levels. The rows indicate the amount of radiation inside a settlement with the given amount of water shielding. The columns correspond to different orbital inclinations at a 600 km altitude. Red indicates that the level meets our 20 mSv/year threshold for adults. The levels reported here are for human tissue in general, not human ovaries as in the other tables. Thus, the levels are not directly comparable to other tables in this paper but the differences are small. Note that the other LEO tables use polyethylene and this uses water. All calculations by OLTARIS.

How Wide is the Low Radiation Window?

Table 5 shows us that at 0 degrees inclination radiation levels are very low and at 15 degrees they are quite high. Table 6 explores the region between these two to determine how close to equatorial an orbit must be to garner the benefits of missing the South Atlantic Anomaly.

500 km	No shielding					
	biological (Dose Equivalent)			physical (Dose)		
inclination	ovaries	All	GCR	all radiation	GCR	Trapped Proton and Neutron Albedo
deg	mSv/yr	mSv/yr	mSv/yr	mGy/yr	mGy/yr	mGy/yr
0	16.77	17.68	16.78	10.23	3.194	7.036
1	16.77	17.68	16.78	10.23	3.194	7.036
2	16.8	17.75	16.81	21.97	3.201	18.77
3	16.83	17.89	16.84	51.31	3.208	48.1
4	16.86	18.25	16.87	97.74	3.215	94.52
5	16.93	18.97	16.91	161.7	3.221	158.5
6	17.22	20.56	16.98	274.2	3.247	271
7	17.88	22.95	17.06	427.1	3.274	423.8
8	19.48	26.96	17.14	656.9	3.292	653.6
9	21.88	31.89	17.27	897.1	3.311	893.8
10	27.34	40.49	17.39	1217	3.33	1214
11	26.58	42.69	17.49	1616	3.358	1613
12	39.55	70.7	17.66	2012	3.388	2009
13	68.8	94.39	17.85	2567	3.422	2563
14	88.04	118.3	18.04	2915	3.462	2912
15	113.1	148	18.27	3270	3.505	3266

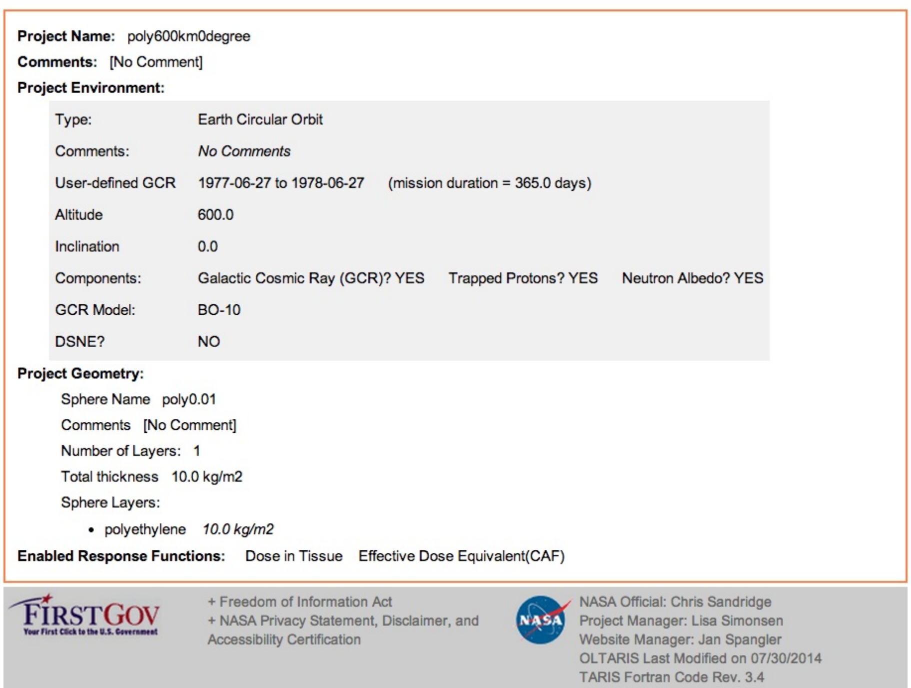
Table 6 shows the nature of radiation near 0 degrees inclination. Red indicates that is matches the 20 mSv/yr adult limit for female ovaries, but in this case not the pregnancy threshold. These data are for a circular orbit at 500 km. Note that the data are identical for 0 and 1 degree. This is because OLTARIS has a divide by 0 when inclination is 0 so it is changed to 1 degree internally [Sandridge 2015]. Shielding is 1 mg lunar regolith per square meter. The first column is the orbit's inclination. The second the absorbed dose for female ovaries. The third the absorbed dose at the center outside the body. The fourth the proportion of the third due to GCR. The fifth is the radiation level, not modified for biological effectiveness. The sixth the GCR part of the fifth and the sixth the trapped protons and neutron albedo for the fourth. All calculations by OLTARIS

Notice that the window of low radiation around 0 inclination is about 8 degrees considering the adult threshold only. This is enough so that launch facilities to support settlements in ELEO can be quite some distance from the equator without much delta-v penalty for inclination change. The Guiana Space Center where Ariane launches, for example, may be within the window. Also note that the GCR component of the radiation rises only gradually with inclination, but the trapped proton and neutrino component increases quickly and dramatically. These particles are easy to shield. The take home message is that low-radiation settlements can be a bit off of zero inclination, but not by much.

Note that the pregnancy threshold is badly violated in this table but this is for essentially no shielding. However, the pregnancy threshold is met for GCR and the trapped protons are easily blocked, probably by the the mass of the hull as needed for the pressure vessel, artificial gravity loads, and micrometeoroid/debris protection.

Method

All of the calculations in this paper were made with OLTARIS. Figure 3 indicates the parameters used for the LEO calculations (except Table 5). Only the material (the "sphere") and the altitude or inclination were changed for each run. For this study, the model calculates radiation for a point in the middle of a sphere of uniform materials and also calculates the biological effect on the ovaries of a woman placed at this point. Figure 4 indicates the parameters used for the free space calculations. Only the material (the "sphere") changed between runs. Calculation results were usually read off the OLTARIS output and entered by hand into a spreadsheet, but for Table 5 the "Copy Data" OLTARIS button was used. Except for Tables 5 and 6, the mSv/year columns always came from the human ovaries results. The response function measured the dose in tissue using the "Computerized Anatomical Female (CAF)" model. The details of what these parameters mean can be found in the help and reference sections of the OLTARIS web site.



Project Name: poly600km0degree
Comments: [No Comment]
Project Environment:

Type:	Earth Circular Orbit
Comments:	*No Comments*
User-defined GCR	1977-06-27 to 1978-06-27 (mission duration = 365.0 days)
Altitude	600.0
Inclination	0.0
Components:	Galactic Cosmic Ray (GCR)? YES Trapped Protons? YES Neutron Albedo? YES
GCR Model:	BO-10
DSNE?	NO

Project Geometry:
Sphere Name poly0.01
Comments [No Comment]
Number of Layers: 1
Total thickness 10.0 kg/m2
Sphere Layers:
- polyethylene *10.0 kg/m2*

Enabled Response Functions: Dose in Tissue Effective Dose Equivalent(CAF)

Figure 3 shows the parameters used for the LEO calculations. Only the materials ("sphere name" which includes the thickness) and altitude changed between runs.

Project Name: FreeSpace
Comments: [No Comment]
Project Environment:

Type: Free Space
Comments: *No Comments*
GCR Model: BO-10
Event 1977 Solar Min (DSNE) (mission duration = 365.0 days)

Project Geometry:

Sphere Name lunar10
Comments [No Comment]
Number of Layers: 1
Total thickness 10000.0 kg/m2
Sphere Layers:

- lunar_regolith_a17 *10000.0 kg/m2*

Enabled Response Functions: Dose in Tissue Effective Dose Equivalent(CAF)

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+ NASA Privacy Statement, Disclaimer, and Accessibility Certification

NASA Official: Chris Sandridge
Project Manager: Lisa Simonsen
Website Manager: Jan Spangler
OLTARIS Last Modified on 07/30/2014
TARIS Fortran Code Rev. 3.4

Figure 4 shows the parameters used for the free space calculations. Only the materials ("sphere name" which includes the thickness) changed between runs.

Radiation in space varies with time. All of these calculations used the same one year time period during the 1977 Solar Minimum, which is a conservative choice for GCR levels as they tend to be high at solar minima. As cosmic radiation during minima is a factor of three or four higher than at maxima [Clement 2012], most other time periods would be expected to generate lower radiation figures.

Note: we report OLTARIS results for 0 degrees inclination orbit as we requested for the computation runs, but internally OLTARIS converts 0 degrees to 1 degree to avoid a divide by zero in the code [Chris Sandridge 2015]. This means that the results presented here are slightly pessimistic, i.e. radiation levels at 0 degrees inclination should be a little lower than those reported here.

Validating the Radiation Model and Thresholds

This study is based on the output of sophisticated radiation models developed by NASA and others. However, models are never completely accurate and the region of space we are interested in does not appear to have received extensive examination. Thus, it is possible the radiation model is not completely accurate.

The OLTARIS LEO radiation model is known to be somewhat inaccurate, and low, for trapped protons and electrons. However, these particles will likely be absorbed by the hull material needed to maintain atmospheric pressure, impact protection, and 1g centripetal force for artificial gravity. The particles of primary interest, relativistic heavy ions, are probably better modelled as the dynamics are much simpler. The ISS data in figure 2 are reasonably consistent with the computational results.

Nonetheless, since so much depends on the exact radiation levels it may be wise to send a small satellite with suitable sensors to the region, say a 450 km by 650 km elliptical orbit with zero inclination. It must have sensors to measure the flux of high energy, high mass particles (GCR) as these are the primary threat. If other sources of radiation can be measured as well (particularly high energy inner belt protons), so much the better.

Conversions of radiation levels to biological effect are much more error prone than the radiation levels themselves. Indeed, for the fetus and embryo it cannot be done at all with current knowledge [Valentin 2003]. Thus, a focused research effort to understand the biological effects of radiation in ELEO is in order, particularly for children and pregnant women. Preparatory work can be done on the ground, but it is impractical to reproduce the relevant radiation environment on Earth. Thus, spaceflight experiments are necessary. This should involve a small animal centrifuge in orbit to control for the effects of weightlessness. Indeed, multigeneration rodent studies are very difficult without a centrifuge as in weightlessness young mice have great difficulty nursing and often simply starve to death [Burgess 2007].

The importance of understanding space relevant GCR doses is hard to overstate. The primary threat is these particles and their biological effect is poorly understood. Most animal studies assume that much higher doses for much shorter periods of time are equivalent to year or multi-year exposures, but that is not necessarily the case. Furthermore, settlers will be exposed not for years but for decades. Understanding these particles should be a primary focus of the proposed research program.

The same studies that examine biological effect can be used to help validate (or modify) the thresholds chosen (20 mSv/year for the general population and 6.6 mGy/year for pregnant women). While the adult general population level is very supported, for children and pregnant women the level will require a great to deal of research and probably need modification. Thus, studies will need to include multi-generational work to look for problems during pregnancy.

The easiest way to conduct such studies is on the International Space Station (ISS), which is available today and can study rodents (among other animals). However, there is no small mammal centrifuge and the ISS radiation environment is much more extreme than in ELEO as the ISS is in a 51.6 degree inclination orbit (see Table 5). If ISS studies suggest that the problems may be unacceptable, then a suitable biological research station in ELEO will be necessary since the effects should be less given the much lower radiation levels found there.

Discussion

The primary interest of the authors is in space settlement. These radiation shielding findings, should they stand up to further investigation, have strong implications for the easiest path to the first settlements and how we might spread throughout the solar system. First we discuss the radiation limits chosen and then settlement mass implications.

20 mSv/year and 6.6 mGy/year Limits

While the 20 mSv/year to ovaries limit should be sufficient to avoid premature sterility there may be more severe than expected problems with birth defects, cancer, cardiovascular problems, central nervous system problems and/or cataracts, all of which can be affected by in-space radiation, although there is reason to believe ovaries are the most at risk. The 6.6 mGy/year limit for pregnant women is much more speculative, although it is well below the thresholds for severe damage observed in rodent experiments and nuclear bomb survivors (see Table 1). Both thresholds are well below background radiation in some inhabited parts of Earth, but the nature of the space radiation threat, primarily high energy, heavy nuclei, is much different than the radiation these thresholds are based on.

However, even if issues arise they may not be sufficiently severe to deter a small fraction of Earth's population from moving into space settlements, and only a very small fraction of Earth's seven billion people are needed. The pull of space settlement can be very strong. For example, a recent call for volunteers reportedly received over 200,000 responses for an extremely risky one-way Mars settlement plan [Mars One 2014] with many respondents even paying a registration fee. Moving from place to place on Earth often involves a significant increase in risk, including background radiation levels, for a variety of reasons and people do it anyway. There is more to life than minimizing radiation exposure.

Also note that the first space settlement will almost certainly not be built for decades, and it is reasonable to expect that at least some of the problems that may arise from low dose continuous radiation exposure will become easily correctable on this time scale. For example, cataracts can be treated effectively today. For many, earlier cataract surgery than expected on Earth may be of minor importance compared to living in space. Also, the risks from space radiation may be minor compared to other threats. All this suggests that thresholds in the neighborhood of 20 mSv/year for the general population and 6.6 mGy/year for pregnant women is adequate to protect inhabitants and allow settlement of the solar system.

Of course, significant additional research in the relevant environment is necessary before construction begins.

Settlement Mass

The result that little or no radiation shielding material may be necessary for settlement in ELEO was surprising to the authors and has far reaching consequences because above the Earth's magnetic field radiation shielding is the vast majority of orbital settlement mass (see Table 7). The exact values in Table 7 are not particularly accurate. For example, the mass of interior furnishings is not included. However, the mass reductions are so enormous that even with inaccuracies it is clear that placing settlements in ELEO requires far, far less materials than in free space.

name	structural mass (tons)	air mass (tons)	shielding mass (tons)	total/non-shielding
multiple dumbbells	75,000	37,000	9,900,000	89
multiple torus	100,000	10,400	9,700,000	89
banded torus	112,000	13,200	7,000,000	57
single torus	4,600	1,900	1,000,000	155
cylinder	775,000	299,000	19,400,000	19
sphere	64,600	35,200	3,300,000	34
dumbbell	400	200	1,400,000	2,334

Table 7: Mass estimates from [Johnson 1975] as a function of settlement shape. The vertical dimension is various possible shapes. The second through fourth column are the mass of the structure, air, and shielding respectively. The last column is the mass reduction factor achieved by eliminating shielding. For example, eliminating the shielding for the cylinder reduces total mass by a factor of 19[9].

With our radiation thresholds the assumption that space settlements need massive shielding requirements falls apart in ELEO. The reason the 1970s studies placed settlements at L5 was proximity to lunar materials which are energetically easier to launch than from Earth. However, eliminating the mass for radiation shielding and moving to ELEO makes launching everything from Earth arguably as easy or easier than delivering a (much larger) settlement worth of lunar materials to L5. Indeed, the energy advantage of Moon launch over Earth launch is about a factor of 19[10], the same as the radiation shielding mass factor disadvantage for the cylinder in Table 7. This means that the total energy to launch an unshielded settlement from Earth to LEO is (very roughly) the same as the energy to launch the materials for a shielded settlement from the Moon to L5.

Moreover, if materials are launched from Earth, one can send exactly what is needed rather than gathering and processing bulk materials from the Moon, reducing the mass of materials launched even more. Compared to the 1970s studies, this also eliminates the entire extraterrestrial mining, processing and manufacturing infrastructure assumed to be necessary to build the first orbital settlements. Taking extraterrestrial mining out of the critical path for the first settlement allows a much more incremental approach to settling the solar system.

One of the weaknesses in the business plans of asteroidal and lunar mining companies is the size of the market. As delivering materials to the surface of the Earth is difficult and involves direct competition with Earth resources on home turf, the ideal market is for utilization is in space. Today that market consists of robotic spacecraft not designed to for repair or refueling and 3-6 people in the ISS. However, once ELEO settlements are in place there will be

[9] The reason the cylinder value is so low is that the cylinder is very large, with a population of 100,000. The other shapes have populations of 2,000-10,000.

[10] When measured by the square of delta-v and only a little higher when measured using the rocket equation assuming high ISP.

hundreds, and eventually many thousands or even more customers in orbit[11]. If realized this presents a market opportunity that could drive the space mining industry. Of course, once ELEO is full lunar and/or asteroidal shielding materials will be critical to provide adequate shielding for new settlements beyond the Van Allen Belts creating a very large market indeed.

With no extra shielding beyond the structure, furnishings and atmosphere, a settlement in ELEO may be vulnerable to particularly large solar flares. Fortunately, at the highest flux levels these are relatively short, usually hours, and dangerous ones are rare [Cucinotta 2012] [Clement 2012]. In a settlement such as Kalpana One[12] [Globus 2007], a low-g cylindrical swimming pool around the axis of rotation can be used as a solar storm shelter. When a solar storm threatens, everyone has to go swimming for a few hours, with short breaks when the Earth is between the settlement and the Sun. The children, at least, should find this mandatory swim party quite acceptable!

Settlements in LEO will be subject to atmospheric drag and without reboost will eventually enter the atmosphere and impact the ground. Fortunately, using electric propulsion for reboost requires little mass due to the high propellant velocities (10s of km/sec). For example, at 20 km/sec propellant velocity the Kalpana One space settlement requires around 2.3 tons/year of reaction mass at 600 km, 8.5 tons/year at 550 km, and 18.7 tons/year at 500 km[13]. This activity does require a great deal of energy.

Heavy objects in the 500 km equatorial orbits take centuries to deorbit if abandoned, leaving ample time to deal with any such event. For example, using the Orbital Lifetime Calculator[14] and assuming a settlement with no radiation shielding and a mass per drag area of 950 kg/m^2, deorbit time is about 195 years for an altitude of 500 km.

Conclusion

The conclusions of this paper should be considered preliminary and subject to revision as more is learned about the human body's response to radiation, particularly low levels of GCR. This is particularly true with regard to pregnant women and children. Studies to resolve these issues are best conducted in equatorial LEO (ELEO), and the ISS may be a "good enough" platform if a rodent centrifuge is added. There is also uncertainty in all models, including those used here, so a radiation measurement mission to ELEO might be in order. However, we believe our findings have a good chance of holding up under further examination.

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[11] If settlements are spaced 1,000 km apart at 500 km there is room for about 40 settlements. If a few nearby orbits are settled it is reasonable to expect up to a few hundred settlements in LEO. If these eventually grow to 10,000 residents or so apiece, the market will consist of a million people or more.
[12] Kalpana one is a 325m long, 250 m radius cylindrical settlement design for a population of perhaps 3,000.
[13] Using the methodology and data at http://spacience.blogspot.com/2012/03/how-to-calculate-drag-in-leo-using.html
[14] http://www.lizard-tail.com/isana/lab/orbital_decay/ accessed on 15 August 2014.

First, it appears that 20 mSv/year and 6.6 mGr/year are reasonable thresholds for a space settlement's general population and pregnant women respectively. This is higher than the average background radiation experienced by most people on Earth, but there are many inhabited parts of the world where background radiation approaches or even exceeds this level.

Second, given these limits, space settlements in ELEO orbits may not require any dedicated radiation shielding at all, or only small amounts. This has strong implications for the location of the first orbital space settlement which, contrary to previous belief, may be easier to build in ELEO using only launch from Earth rather than depending on extraterrestrial mining, processing and manufacture for bulk materials. This is because of the shielding provided by Earth's magnetic field and by the Earth itself. Of course, a settlement in ELEO is better positioned for commerce with Earth than settlements in higher orbits or on the Moon or Mars.

Acknowledgements

Our deepest thanks to the OLTARIS team for their excellent easy-to-use system, rapid response to problems, and patient explanations. This study could not have been done without them. It should be noted that OLTARIS is available to US citizens and legal residents at no charge. Thanks to Tom Krehbiel for comments. Special thanks to David Brandt-Erichsen for proofing and editing.

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